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PRELIMINARY SEISMOLOGICAL AND GEOLOGICAL STUDIES OF THE SAN FERNANDO, CALIFORNIA, EARTHQUAKE OF FEBRUARY 9 1971

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The San Fernando earthquake was the largest earthquake to occur in the metropolitan Los Angeles area in more than 50 years. It has tentatively been assigned a magnitude, M_L of 6.6, a focal depth of 13.0 km, and an epicentral location about 12 km east of Newhall, California, at 34°24.0'N, 118°23.7'W (Figure 1), but these figures undoubtedly will be modified as further data become available. Although the focal depth is not as well defined as the epicenter, it is consistent with other observations suggesting thrusting on a fault plane dipping north about 45° and breaking the surface in the Sylmar-San Fernando area (Figure 1). It should be emphasized that the hypocenter of the main shock represents only the point of initial rupture. Breaking, presumably, then propagated southward and upward from this point, so that the main geological and engineering effects were observed farther south where the fault was shallower and the displacement greater. The location of the main shock is based on readings from permanent stations of the Caltech network, as well as the U. S. Geological Survey station at Point Mugu (SBLG) and the California Department of Water Resources stations at Pyramid (PYR) and Cedar Springs (CSP). Portable Caltech seismographs were installed in the epicentral area as early as 3 hr following the main shock, and, within a few days, there were at least 30 portable units in the region operated by various groups and agencies.

Figure 1 shows the location of the San Fernando earthquake and some of its aftershocks in relation to geographic features and to traces of surficial fault movement, which are shown in greater detail in Figure 2. Through February 23rd, 199 aftershocks of magnitude 3.0 or greater had been identified, and the list is felt to be relatively complete following the first hour of activity; only those shocks for which adequate computer solutions have been obtained, thus far, are shown in Figure 1. The 26 shocks of magnitude 4.0 and greater are listed in Table 1. The aftershock sequence, thus far, appears to be a normal one. There were no identifiable foreshocks or other obvious precursory activity.

The greatest concentration of aftershock activity lies roughly in the shape of an inverted "U" symmetrically disposed both with respect to the epicenter of the main shock and to the surface faulting (Figure 1). It is tempting to suggest that this pattern reflects the boundary of slippage on a north-dipping thrust, but depths of aftershocks obtained to date do not portray such a simple picture. In addition to the routinely determined aftershock epicenters, hypocentral locations have been determined for 25 aftershocks using both P and S readings from 6 portable Caltech seismographs in the epicentral area, a backpack unit installed by Dr. James Brune, and the permanent stations at Pyramid and Mt. Wilson. A typical determination is based on seven P readings and three S readings; generally two or more stations are within 10 km of the hypocenter. We believe that the epicenters of these events are determined within 1 km and the depths are determined within 2 km, except for shallow events (less than 4 km). The deepest of these 25 aftershocks is at 13 km, and the average depth is close to 7 km. Ten aftershocks within 5 km of the epicenter of the main shock have depths ranging from 6 to 11 km. One group of seven aftershocks located 10 to 15 km north of Sunland (Figure 1) are all shallow. Perhaps, as has been observed in other aftershock distributions associated with thrust faults, the bulk of aftershocks occur within the upper plate, which typically is more broken up and shattered than is the underlying block.

Our observations of the pattern of ground breakage by faulting are shown in Figure 2. Only fault traces thought to be tectonic in origin are shown. The faults fall into four groups: (1) West of Pacoima Wash, a line of faulting with prominent left-lateral displacement, trending generally east; this has been informally named the "Sylmar fault segment" by U.S. Geological Survey geologists. (2) East of Pacoima Wash, a line of faulting at the south edge of the Little Tujunga foot-

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hills, trending S80°E, and informally named the "Middle Ranch fault segment." (3) A group of shorter fault breaks subparallel to the Middle Ranch fault segment, in a zone lying 0.2 to 1 km to the north, within the foothills. (4) A small break 1 km east of the Veterans Hospital, just west of the mouth of Pacoima Canyon.

The faults of groups 1 to 3 form collectively a zone (informally named the "San Fernando fault zone") that extends with overall trend S72°E from Sylmar for a distance of 8 km, with small, intermittent indications of ground breakage continuing 2 km farther east. An additional local indication of fault motion along this zone, a left-lateral displacement of 1 m occurs in Big Tujunga Wash, 1.2 km east of the edge of Figure 2. If this is included, the total lateral extent of surface faulting

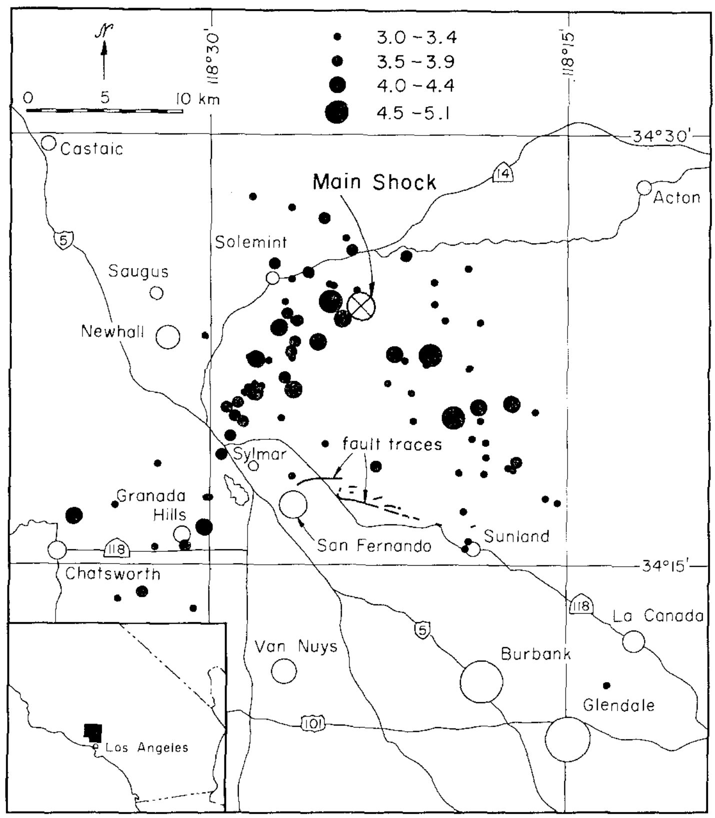

FIG. 1. Map of epicenters of the main shock and representative aftershocks of the San Fernando earthquake of magnitude 3.0 and greater, through February 23 1971.

is about 12 km, and is comparable to the distance of about 12 km from the surface breaks to the epicenter of the main shock.

The maximum displacements observed along the main fault breaks, expressed in meters, are shown in Figure 2. Displacements are given in terms of the three slip components: vertical, lateral (horizontal component parallel to strike of fault plane), and transverse (horizontal component normal to strike). The *arrow* specifying the transverse component shows the motion of the south side relative to the north side.

The displacements of the faults in groups 1 to 3 are grossly similar in that all involve significant amounts of north-south compression, or uplift (north side up), and of left-lateral motion. The three components are of comparable magnitude, and the gross differential motion can be represented as a thrusting of a northern block southwestward over a southern block, through a maximum distance of 1 to 2 m, along a fault plane dipping about 45° toward N20°E. This over-all surface motion agrees reasonably well with that inferred from the fault-plane solution for the main shock (Figure 3). In detail there are, however, large local departures from this over-all movement. While the Sylmar fault segment is distinguished by prominent and consistent left-lateral displacement,

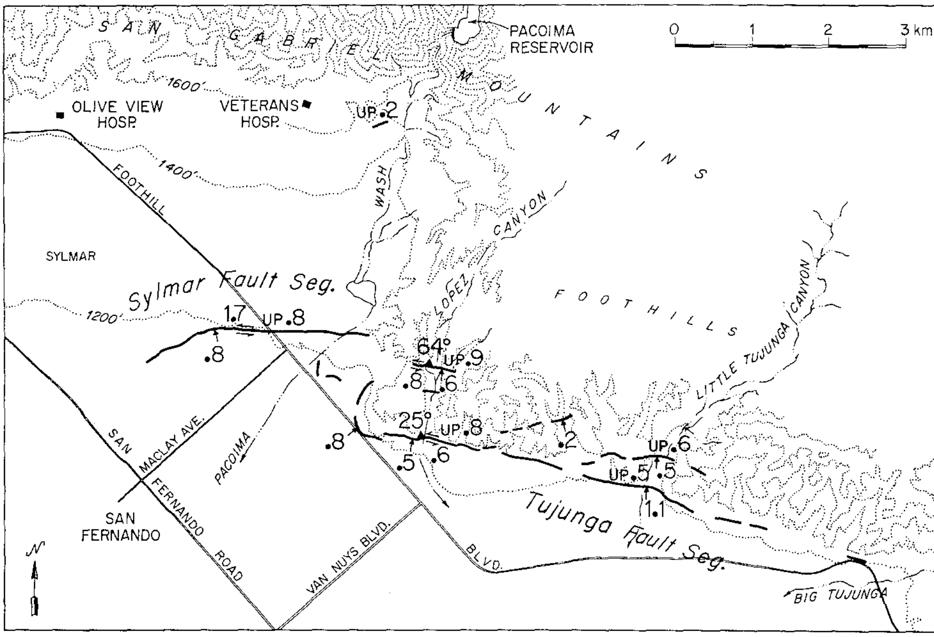

FIG. 2. Surface faulting (*heavy lines*) in the San Fernando earthquake. Maximum observed slip for each main fault segment is given in meters. Vertical slip component is indicated by "*UP*" on upthrown side, lateral component by *half-barbed arrows*, and transverse component by an *arrow* showing direction of movement of southern side relative to northern. Dip of fault surfaces is indicated opposite the *solid triangles*.

TABLE 1

SHOCKS OF THE SAN FERNANDO SERIES OF MAGNITUDE 4.0 AND GREATER, FEBRUARY 9 THROUGH 23 1971*

Date	Time (GMT)	M_L	Latitude N	Longitude W
Feb. 9	1400 41.6	6.6	34°24.0′	118°23.7′
	1401	5.1		
	1402	4.4		
	1403	4.5		
	1404	4.3		
	1406	4.2		
	1407	4.5		
	1410 21.5	5.1	34°21.7′	118°18.4′
	1416	4.2		
	1419	4.4		
	1434	5.1		
	1443 46.6	5.2	34°18.5′	118°27.2′
	1510 01.1	4.1	34°23.7′	118°24.5′
	1538 29.7	4.2	34°21.0′	118°28.1′
	1558 20.7	5.1	34°20.1′	118°19.8′
	1619 26.0	4.3	34°16.7′	118°35.7′
	1857 02.4	4.0	34°20.7′	118°17.3′
Feb. 10	0138 15.6	4.0	34°16.3′	118°30.2′
	0312 11.9	4.0	34°20.5′	118°18.7′
	0506 35.8	4.6	34°22.4′	118°20.8′
	0518 07.0	4.6	34°24.3′	118°25.0′
	0727 03.2	4.1	34°21.1′	118°26.5′
	1349 53.6	4.2	34°22.8′	118°25.5′
	1738 54.9	4.3	34°22.4′	118°22.3′
	1854 41.5	4.1	34°23.4′	118°27.1′
Feb. 21	0550 52.3	4.0	34°22.2′	118°28.1′

* Magnitude assignments, in particular, are very tentative. Depths are restricted to 8.0 km, except for the main shock, which is at 13.0 km.

the Middle Ranch segment, and the faults of group 3, show smaller and less consistent lateral motion, with right-lateral motions up to 0.2 m observed locally.

The fault traces of groups 2 and 3 are either clear fault scarps, or are zones of ground displacement and disruption a few meters wide. In contrast, group 1 is represented in detail by a zone of deformation distributed over a width of about 50 m. Within this zone are many sharp breaks in pavement, but unpaved ground shows relatively continuous deformation, with few clear scarps or "mole tracks." This contrast reflects the underlying geology. The trace of the Sylmar fault segment is wholly within the broad alluviated valley west of Pacoima Wash, whereas the foothill area of group 3 is underlain by Tertiary sediments (Oakeshott, 1958). The Middle Ranch fault segment lies at or very near the contact between these sediments and Quaternary alluvium to the south.

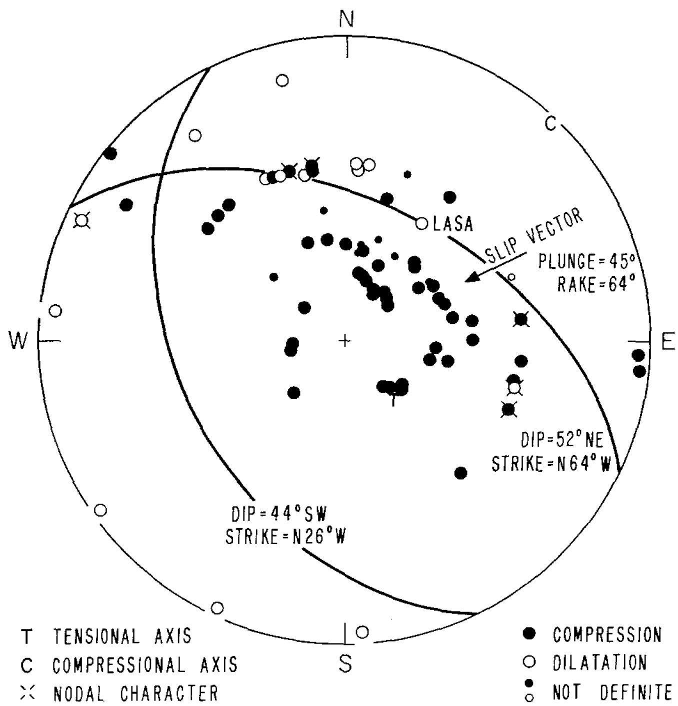

FIG. 3. Focal mechanism solution for main shock of the San Fernando earthquake. Equal area projection of P-wave first motions on lower focal sphere. Take-off angles were calculated using a crustal model with the CIT208 P-wave velocity model and a focal depth of 14 km. Readings were made by the authors for southern California stations and were kindly provided by numerous sources for the remaining stations. A complete listing of all readings is available on request.

From the pattern of the fault trace where it crosses canyon mouths, the Middle Ranch segment appears to dip 20° to 25° north, shallower than what is suggested by the relative amounts of vertical and transverse slip. The best exposed fault surfaces of group 3 dip about 65° north, and the surfaces are here parallel to bedding in the Tertiary sediments. No observation of the attitude of the Sylmar fault segment was possible.

The fault placed in group 4 is of special interest because, although small, it is the only example that we have found of a tectonic fault displacement in the area of greatest ground shaking, along the San Gabriel Mountain front where the severely damaged Olive View and Veterans Hospitals are located. It is a reverse fault dipping 61°N, and bringing sediments of the Plio-Pleistocene Saugus formation over old Quaternary terrace gravels. Like the faults of groups 3, it has bedding-plane orientation with respect to the underlying Tertiary sediments. The tectonic nature of the 0.2-m displacement that occurred in the earthquake is corroborated by D. O. Asquith and F. B. Leighton (personal communication).

Although the over-all fault motion is of a type expected in the Transverse Range structural province, the fault lines shown in Figure 2 do not correspond with the traces of bedrock faults shown in recently published geological maps (Oakeshott, 1958; Jennings and Strand, 1969). However, a fault corresponding closely to the Middle Ranch segment was identified by W. J. Miller (1934), probably on the basis of the topographic break at the foot of the Little Tujunga foothills. If the southwest-trending westernmost portion of the Sylmar fault segment were prolonged 1.6 km farther southwest, it would connect with the (queried) trace of the Mission Hills thrust identified by Oakeshott (1958). Consistent with the thrust component of motion and the high intensity of ground shaking near Olive View and Veterans Hospitals, motion might have been expected on the Hospital fault, a thrust dipping 45° north and bringing crystalline basement rocks over Pleistocene sediments along the foot of the San Gabriel escarpment about 0.8 km north of the hospitals (Oakeshott, 1958). The only indication of such motion is the small fault of group 4. But this fault lies 0.5 km south of the probable trace of the Hospital fault at the contact between crystalline rocks and Tertiary-Quaternary sediments.

We have searched the area north from Figure 2 to the epicenter of the main shock, and in particular have examined the Soledad and Pole Canyon faults (near whose intersection the epicenter lies) and the San Gabriel fault. We find no indication of displacement on these faults in the San Fernando earthquake. A reasonable model of the earthquake is a combined thrust to strike-slip displacement occurring initially at a depth of about 12 km under the epicenter, and propagating southward to the surface along a fault plane dipping on the average about 45°N.

Figure 3 shows the fault-plane solution calculated from P-wave first motions plotted on the lower focal sphere. With the assumption of a double-couple mechanism, the two thrust planes derived have the parameters: strike = N26°W, dip = 44°SW, and strike = N64°W, dip = 52°NE. The latter is the preferred fault-plane choice based on the observed surface faulting. The slip vector in this plane is shown in the figure and defines movement with a plunge of 45° and a rake of 64°. Thus, the ratio of throw or vertical motion to strike-slip is predicted to be about 1.6 to 1. A projection down the calculated fault plane from the observed surface faulting towards the hypocenter yields a focal depth of about 15 km for the initiation of the main shock.

The earthquake was well recorded on the quartz strain seismometer and mercury tiltmeters at Isabella, California, 147 km north of the epicenter. A "permanent" offset, corresponding to a release of compression, occurred on both the NW and NE components of strain. A permanent tilt was recorded in the NW direction. These observations are consistent with the strain release that is inferred from the fault-plane solution and surface breakage.

Acknowledgments

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